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Leveraging inter-industry spillovers through DIY laboratories: Entrepreneurship and innovation in the global bicycle industry

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ABSTRACT

DIY laboratories have the potential to advance new technologies, products and services through the leveraging of low-cost facilities by entrepreneurial individuals. We add to this emerging understanding of the DIY phenomenon by investigating the prevalence, operations and contextual factors that impact the use of DIY laboratories in the bicycle industry. We find two contexts in which DIY laboratories are utilised to develop component-level innovations: first, DIY laboratories are utilised as a low-cost way to enter an industry where the entrepreneur lacks the necessary financial resources and rely upon bootstrapping to build their enterprise. Second, and more frequently, DIY laboratories were used for the integration of diversified technical knowledge originating in other industries. Our study highlights the important role that DIY laboratories may play in leveraging inter-industry knowledge spillovers whereby DIY laboratories operate as incubators in the repurposing of diversified knowledge from high-technology sectors to lower-technology sectors to generate incremental innovation. Further, the modular product architecture of the bicycle helped facilitate the co-opting of technical knowledge prevalent in other industries by allowing entrepreneurs to focus their product development and subsequent commercialisation activities at the component level of the product artefact.

1. Introduction

Technological innovation has long been linked to firm performance and economic growth (Andersson et al., 2018; Klarin, 2019; Li et al., 2020; Tian et al., 2018). How this innovation occurs has been the subject of different models such as technology-push versus market-pull (Arthur, 2009) along with considerable analysis of the processes and the actors involved leading to different foci over time ranging from alliances and inter-organisational networks to open innovation, and the study of institutional factors (Christofi et al., 2019; Nylund et al., 2020; Rice et al., 2012). In addition to this burgeoning literature, DIY laboratories (hereafter referred to as 'DIY labs') have recently emerged as a new and rapidly-growing phenomenon that may expand the pace and scope of technological advancement (Gorman, 2011; Hecker et al., 2018). The emergence of the DIY phenomenon is at least partially fuelled by technological advances such as increased computing power and other affordable technologies that allow research and development to be undertaken in small-scale locations such as garages and workshops, rather than traditional corporate or state-sponsored research environments (Nascimento et al., 2014).

Much of the existing DIY labs literature has emphasised the motivations, characteristics, background, and expertise of individual entrepreneurs, hobbyists, engineers and designers (Baden et al., 2015; Hatch, 2013; Martin, 2015). However, existing literature has largely disregarded the shape and influence of the technological and institutional contexts in which DIY labs may emerge and prosper. Perhaps one possible explanation for this focus is that the DIY labs phenomenon has not yet attracted widespread interest in the management and organisation literature, despite considerable attention in scientific and engineering journals (Fox, 2013; Howard et al., 2019; von Briel et al., 2018). Given the infancy of the research field from a management perspective, when and how DIY labs emerge in a particular institutional context, the role that they play as potential innovation incubators, and how the technological and institutional conditions determine what types of innovation are developed represent significant gaps in the extant literature. We thus seek to advance scholarship in this domain by addressing how DIY labs are utilised and the key contextual factors that impact their role in supporting the development of product innovation.

To signpost our contribution, we draw upon the knowledge spillover theory of entrepreneurship (e.g., Acs, 2010; Acs et al., 2013;

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Agarwal et al., 2010; Plummer and Acs, 2014) to examine the emergence and utilisation of DIY labs by entrepreneurs in the global bicycle industry. As knowledge spillovers address the non-purposeful movement of knowledge across organisational boundaries through means such as the loss of key personnel, reverse engineering of products and even corporate espionage (Shu et al., 2014), DIY labs may be utilised in the leveraging of knowledge spillovers from incumbent organisations to new start-ups. Critically, these DIY operations may play an ‘incubator’ role that facilitate the development of future organisational or industry spin-offs, and stimulate new products or processes (Chen and Choi, 2004). As such, our analysis seeks to illuminate the inter-industry knowledge spillover role that DIY labs play in repurposing knowledge from high-technology sectors and driving forward innovation in a recipient sector. As part of this investigation, we considered the outputs of these DIY labs in terms of the types of innovations generated and the role of technological and contextual factors (e.g., product architecture) in allowing DIY labs to provide an effective entry point for new entrants to deliver exaptive innovations into the bicycle industry.

2. Literature

DIY labs are a new and rapidly-growing phenomenon with expanding legitimacy having featured in both science/engineering as well as business research (Fox, 2014; Hecker et al., 2018; Kwon and Lee, 2017; Sarpong et al., 2020). DIY science is broadly defined as the process whereby individuals and groups out of their own need, curiosity or interest, innovatively develop, recreate or fix objects and systems from their own spaces and share the outcomes in different ways (Ferretti, 2019; Nascimento et al., 2014). Gorman (2011) highlights that the process involves scientists and developers conducting research and product development from homes and other non-traditional venues. However, the DIY organising logic may apply to corporate settings where employees are provided access to open laboratories that allow interaction with enthusiasts from outside of the organisation to help generate new solutions to existing problems (Fritzsche, 2018). One of the challenges in clearly defining DIY labs is the heterogeneity of definitions and the way that it is viewed in practice across different contexts. It has been variously applied to different actors ranging from individuals, small groups of tech enthusiasts or entrepreneurs, to large online or physical communities, and activities that span a number of different disciplines such as engineering, science, and education – each with their own unique characteristics (Aldrich, 2014; Ferretti, 2019; Landrain et al., 2013).

Much of the DIY innovation literature focuses on individual entrepreneurs, hobbyists, engineers and designers in respect of how they innovate and create new products (Baden et al., 2015; Hatch, 2013; Martin, 2015). Driven by intrinsic motivations such as the passion and enjoyment of the entrepreneur (Gerschenfeld, 2008; Hurst and Tobias, 2011; Kalil, 2013), the growth in DIY labs can be at least partially explained by the increasing affordability of technical equipment that may be used. The development activities typically take place in non-traditional locations ranging from home garages to communal workshops, and whilst a variety of locations and facilities are provided in various examples in the literature, the key feature would seem to be that the research and development opportunities present in such locations differ considerably from corporate or state funded laboratories at universities or other research institutions that have a defined research programme (Nascimento et al., 2014). Similarly, funding tends to be drawn from outside the traditional funding channels, such as self-funding, crowdfunding, non-profit organisations or communal sponsors (Aldrich, 2014; Schön et al., 2014).

Overall, the technological or institutional factors that encourage the emergence of the DIY labs phenomenon has been surprisingly disregarded in the existing literature, albeit with a few notable exceptions. For instance, DIY labs are often associated with radical or breakthrough innovations (e.g., Aldrich, 2014; Anderson, 2012; Von Hippel 2005).

Such radical innovations emerging from DIY labs contribute to the emergence of new sub-industries, as shown in cases concerning medical devices, extreme sports gear and typesetting industries (Aldrich, 2014; Gorman, 2011; Nascimento et al., 2014). At the institutional level of analysis, Fu and Lin (2014) noted how the shift to platforms in a number of industries has allowed for individuals to engage in ‘participatory research’ which in turn has contributed to successful entrepreneurial start-ups such as Pebble, Makerbot, and Square in Silicon Valley. Likewise, Kwon and Lee (2017) acknowledge that technological and institutional changes have substantially reduced the barriers for entrepreneurs to engage in start-ups through DIY labs across many industries and that changes in traditional industry structures may provide increased opportunities for radical innovations by these entrepreneurs (Sarpong and Rawal, 2020). These opportunities are reinforced via the availability of new technologies that can operate in DIY spaces, enabling entrepreneurs to set up their businesses with far fewer resources (Hatch, 2013; Schön et al., 2014). This democratisation of scientific investigation, innovation and new product development through DIY labs represents a “cultural trend that focuses on an individual’s ability to be a creator of things using technology” (Kwon and Lee, 2017: 318).

Whilst DIY labs research to date has tended to address the ‘who’ and ‘where’ questions, we turn to the knowledge spillover theory of entrepreneurship to illuminate ‘how’ knowledge and capability spillovers across both firms and industries to enable individuals to become a ‘creator of things’ (Acs et al., 2013; Ghio et al., 2015; Plummer and Acs, 2014; Venturini et al., 2019). The theory posits that knowledge produced in a given technological context remains within that same context, reinforcing the existing technological trajectory and constraining technological variety (Battke et al., 2016; Schoenmakers and Duysters, 2010), leading incumbent firms to focus on only the familiar technological landscape (Aharonson and Schilling, 2016). The transmission of knowledge spillovers are “informal, unintentional and uncompensated transfers of knowledge” (Isaksson et al., 2016: 700) that occur when the technology or scientific knowledge developed by an incumbent firm is appropriated by a third party, often a new venture or start-up, without proper economic compensation (Acs et al., 2009; Chen and Choi, 2004; Kafouros and Buckley, 2008). It is this shift in the potential use of the knowledge outside of its existing technological domain that presents opportunities for radical or discontinuous innovation (Acs et al., 2013).

Spillovers may arise in horizontal contexts - when the incumbent and recipient firms operate in the same technological domain - or in vertical contexts - when the incumbent and recipient firms operate in different technological domains (Kaiser, 2002; Montoro-Sánchez et al., 2011; Stephan et al., 2019). In either case, knowledge spillovers occur when the knowledge created by the incumbent firm is not fully appropriated or commercialised, and leaks to another organisation in various ways such as scientific publications, reverse technological engineering, inter-firm collaborations, or through the loss of valuable human capital such as scientists and engineers leaving their existing organisations to pursue new opportunities (Shu et al., 2104). It is these “opportunities stemming from knowledge generated and not commercially exploited by incumbent firms or academic research institutions” that may then be developed by entrepreneurs (Ghio et al., 2015: 2). These opportunities may often constitute exaptive innovations – the process by which technologies developed for one purpose are repurposed for an entirely different role (Andriani et al., 2017).

In leveraging knowledge and technology spillovers, entrepreneurs may find DIY labs are able to play an ‘incubator’ role that facilitates the development of future organisational or industry spin-offs, and stimulates new products or processes (Chen and Choi, 2004). Rather than conceptualising knowledge spillovers as lost opportunities for incumbent firms, it is possible to focus instead on the transformation of knowledge into innovation as the challenge facing most organisations, thereby recognising that firms will not be able to exploit all opportunities that their knowledge base provides them into commercialised

innovations (Block et al., 2013). It is these uncommercialized opportunities that potentially provide the ‘intellectual fodder’ for DIY labs to act as an incubator for the development of small, entrepreneurial and often, high-technology firms (Chen and Choi, 2004; Montoro-Sanchez et al., 2011).

Whilst all firms may have a portfolio of non-commercialised knowledge that has not been translated into innovations, it has been shown that the higher the level of R&D activities in a sector, the more knowledge is produced, and the greater the level of knowledge which remains unexplored and could potentially be exploited by new entrepreneurial ventures (Acs et al., 2013). Knowledge created through R&D and the subsequent innovations originating in sectors such as metals, aerospace, and chemicals are thus often described as hubs or ‘superspreaders’ (Semitiel-Garcia and Noguera-Mendez, 2012) from which knowledge more-readily diffuses to other industries to spur technological advances in a recipient sector. In respect of knowledge spillovers, much research has relied upon quantitative measures such as patents, suggesting that high technology sectors (that tend to utilise patents) tend to be key drivers (Berg et al., 2019; Suh and Jeon, 2019). However, while some knowledge may be codified (which may be captured in patent counts etc.), other knowledge is tacit in nature (which may be better observed in processes or routines). Thus, industries that do not feature easily measurable explicit knowledge may be under-represented in their impact on the number of new start-ups due to the difficulty in capturing the more tacit forms of knowledge that may spillover into entrepreneurial start-ups (Audretsch and Lehmann, 2005). In the context of DIY labs, we presently know relatively little about the types of organisations from which knowledge spillovers emanate, the processes that facilitate inter-industry knowledge spillover from source to recipient industries, and how technological and institutional contexts shape the leveraging of such spillovers. This leads us to propose two research questions:

RQ1: What role do DIY labs play in inter-industry technology and knowledge spillover?

RQ2: How does the technological and institutional context affect the type of innovations that emerge?

3. Research method

The data used in this paper comes from a study of the global bicycle industry covering significant innovations that have emerged across the industry between the late 1970s and 2010. The global bicycle industry features very high levels of innovation at the product level and in respect of many of the processes used in the development of components. The driver of this innovation often tends to be performance-related rather than cost minimisation. As an industry that services a competitive sport in which small improvements can represent the difference between winning and losing, there is a constant demand from the very high end of the market for innovative components that drive performance outcomes. Over time, many of these innovations diffuse through the industry to the mass-market (Yan and Hu, 2008).

The industry is dominated by relatively small specialised firms, often entering the industry on the basis of a single innovative product (Isely and Roelofs, 2004), and as such, this is an industry where the use of DIY labs for some innovation activities may prosper, given the specialization of many firms and the absence of consolidation in the industry. The potential for DIY labs is extenuated by the fact that while there is a high demand for innovative products from the retail market, the financial resources and R&D of most specialised firms is limited and therefore, reliance upon knowledge spillovers and technology appropriation from more R&D intensive industries is possible.

The data for this study was collected through an ‘analytically-structured history’ (Rowlinson et al., 2014) of the global bicycle industry with data being collected from archival sources in two separate tranches. A database was initially created covering all identified

product innovations in the industry from approximately 1980 to 2010.¹ Following an extensive search, the database included trade publications, industry magazines (servicing industry participants and consumers) and books about the industry. A full list of the different publications used is provided in Appendix 1. This list of innovations was then sent to two industry participants with a deep knowledge of the industry to check that no significant innovations had been missed. This first stage resulted in a total of 203 innovations.

In the second stage of the data collection process, mini-case studies were developed for each innovation – who was involved, how was the innovation developed, where was it developed and who was involved in the commercialisation process. The database was supplemented by drawing upon company websites, bicycle history websites, books, newspaper articles and where necessary, interviews with people in the industry. A total of nine short interviews were conducted. These supplemented the archival data, but also provided a useful checking mechanism that helped gauge the accuracy of key archival sources (King and Horrocks, 2010). Detailed information about the innovation and its genesis was available for 98 innovations – which became the final sample.

Within the original list of 203 innovations, there were numerous examples of knowledge spillovers from different industries when people left large corporate firms and set up a firm producing bicycle components. However, for 105 of these innovations we were unable to collect significant evidence about their development. For example, we found examples of where a major aircraft development schedule ended (eg the Boeing 777), large numbers of skilled engineers and machinists were let go. These people had experience with alternative materials (eg, carbon fibre, titanium, billet aluminium), many understood principles around wind resistance, drag, lift, etc. and some entered the bicycle industry producing specialty components. However, the data was limited on where and how the innovation occurred, and we have omitted these cases from our study.

The 98 case studies for which detailed information was able to be sourced were then analysed along three different dimensions. The first was to assess the use of DIY labs. In making this determination, we used the following criteria:

- (a) The location of the work leading to the innovation was at the home of at least one of the innovators such as a garage, basement, home workshop etc., or
- (b) The location was a workshop away from home, and the enterprise was run by a single person or a family to serve an unrelated industry. Any ‘tinkering’ or experimentation thus occurs outside of their regular activities such as nights and weekends.

By applying these criteria, we identified 15 innovations that could be determined as a DIY lab innovation. In comparison, the other 83 innovations in our sample were developed through traditional corporate innovation efforts.

Next, we considered the ‘source’ of the innovation in terms of who was involved, their background, their prior involvement in the bicycle industry and how they were able to turn the initial idea into reality

¹ A start date of 1980 was chosen as this saw the resurgence in interest outside of Western Europe in bicycle racing as a sport (both for spectators and for participants who may ride in groups using basic race-level bicycles). For example, interest in the USA grew after Greg LeMond won the World Championship road race in 1983 and was the first American to win the Tour de France in 1986. Mountain biking also emerged in the late 1970s in the hills around San Francisco. These two trends saw a massive growth in the rate of innovation and change across the bicycle from a product that had barely changed over the previous 20 years. The end date of 2010 was chosen as collecting data after this date became difficult due to the time lags in publishing relevant information in various materials such as books and hardcopy trade catalogues.

(including the physical location of key activities). Finally, each innovation was assessed in terms of the type of innovation that was developed using the Henderson and Clark (1990) typology to allow us to appreciate the prevalence of radical innovations, relative to incremental, modular and architectural innovations. All of the 15 innovations developed through DIY labs were classified as incremental.

Historical research has an important role to play “for investigating the context of contemporary phenomena ... identifying sources of exogenous variations, developing and testing more informed causal inferences and theories ...” (Argyres et al., 2019: 2). While historically oriented research is often reliant upon primary data, there are examples where published secondary/archival sources have formed the principal source of data including case studies concerning the development of the turbojet (Carignani et al., 2019) and the development of the atomic bomb via the Manhattan Project (Gillier and Lenfle, 2019). Whilst interviews are commonly used in historical research, they are invariably constrained by subjectivity such as respondent's own involvement in events and the contextual interpretation that this brings. As such, the benefit of archival sources for this research are threefold; (i) they provide opportunities to review innovations that were never very successful and would most likely be forgotten in a retrospective review of innovations across the industry covering the past two decades or more, (ii) the archival sources provide interpretations of events at the time and reduce the likelihood of certain events being retrospectively rationalised or even ignored given subsequent events, and (iii) the archival sources provide the context of the period.

In the Findings to follow, the data is presented in ‘blocks’ discussing innovations concerning different components in the bicycle. Different components draw upon different types of materials for production, different production processes and feature different firms. For example, frame innovations tend to rely largely upon new materials and different designs. In comparison, moving part components (e.g. gears and brakes) tend to be driven by larger firms and are primarily driven by greater precision, weight considerations and longer lasting sub-components such as sealed bearings. Presenting the data this way is designed to highlight the differences in innovation processes that are present across the dataset. The findings are thus presented under the categories of ‘hubs and wheels’, ‘frames’, ‘moving components’ and ‘other’ such as saddles, handlebars, seat-posts etc.

4. Findings

4.1. Industry background

Following a period of industry decline that coincided with the growth of the motor vehicle in the early 20th Century, the industry began to grow again in the 1960s, and by the 1980s it had regained much of its popularity (Beeley, 1992). The sport of bicycle racing started being televised outside of Europe and ‘middle-aged-men’ took to the sport in increasing numbers as a social form of exercise (Petty, 1995). With this growth, smaller specialised firms started to develop a range of components to sell to frame-manufacturers. These components needed to be able to ‘mix and match’ with as many frame-manufacturers as possible and so the industry started to shift towards a range of industry standards to connect components together (Dowell, 2006). These industry standards eventually reduced over time, and today the bicycle has a modular architecture with components linked together via a limited number of widely-dispersed industry standards (Galvin, 1999; Galvin and Morkel, 2001). There has been a limited movement back towards less modularity in some components such as the drive train in the case of Shimano (Fixson and Park, 2008). With no single firm able to produce an entire bicycle, the industry is populated by specialised firms that are spread across a wide range of countries. While the production of components for performance-related components is dominated by firms in Western Europe, Japan, USA and Taiwan, there are manufacturers in other regions such as South

America, Oceania and Eastern Europe, along with a very considerable number of value-based producers through China and other parts of Asia.

4.2. Hubs and wheels

Many innovations concerning hubs and wheels were developed by incumbent firms in the industry using traditional R&D processes. New materials such as titanium and carbon fibre in the hubs often emerged from firms with significant experience and competencies in this area. Many of the firms operating in the hub and wheel components were very small and highly specialised, and a number entered the bicycle industry on the basis of incremental innovations. Despite the prominence of corporate R&D relating to this component type, we found examples of DIY lab activity.

Leight Saergent moved from Australia to undertake further study in England and was subsequently employed in the Williams Formula One team. He then moved to Indiana with an Indy car racing team, but after the team folded, he set-up a small workshop facility doing Indy car body repair work and building nose boxes and wings for race cars. He initially looked at using his technical knowledge relating to carbon fibre construction to build a racing wheelchair, but after a race car client, who was also a keen cyclist, showed him a disc wheel, he moved to designing a carbon fibre disc wheel. Commercialising the product under the name of Zipp, today the company is one of the largest firms producing carbon fibre discs and other aerodynamic wheels.

The other key innovator in disc wheels was Steve Hed. Initially he developed products for the skateboard and water-ski industries (where he worked with fibreglass and started to experiment with carbon fibre), before his interest in cycling saw him open a bike shop. The development of the disc wheel occurred in his garage and was used initially in professional Ironman races by his future wife, Anne Hed. Together they used the prize winnings from one race to secure a loan of \$14,000, which allowed them to move beyond the prototype Anne was using and started commercial production of carbon fibre disc wheels under the brand name of HED.

Phil Wood was the developer of the sealed bearing used in just about all hubs today except the very cheapest end of the market, though he never patented the idea and never became rich. After a stint in the US Navy, he enrolled in the California Institute of Technology, but dropped out and went to work as a mechanical engineer for FMC. Tinkering with hubs on weekends after racing at the local velodrome led him to develop a sealed bearing hub in his home workshop. Expecting to sell a maximum of 50 hubs per year via people he knew, Wood did not transition to the bicycle industry full-time until he felt assured that the product would be successful.

4.3. Frames

Traditionally bicycle frames have been made from steel and innovation tends to occur in terms of the design, such as different angles and the types of tubing used. For example, (what became) Rock Lobster bicycles are event-specific in terms of design (ie different track cycling events, different events on the road). The founder of Rock Lobster, Paul Sadoff, started working for a local bike shop whilst competing. He then started building frames out of the garage of a property where he was renting a room. He continued to operate out of different garages as he moved around, including that of his then girlfriend before she kicked him out after two years. After a stint in a concrete outbuilding on a ranch, he applied for a business license, a full ten years after his first frame was produced and quit his other work to focus entirely upon frame-building under the name of Rock Lobster which has subsequently produced frames for Olympic and world championship teams.

One company has been particularly successful at designing products for women – recognising the physiological differences between men and women. Georgena Terry completed a liberal arts undergraduate

degree and then an MBA before returning to university studies to complete a degree in mechanical engineering. Working initially at Westinghouse Electric and then Xerox, Terry had simultaneously taken on a hobby of building bicycles for friends out of her basement. After two years with Xerox, she left the company to found Terry Bicycles which produced bicycles that accounted for male-female differences (such as leg length as a proportion of total height). Her company subsequently developed a range of female specific products such as saddles and cycle clothing.

In terms of alternative materials, titanium has been used extensively in weight-bearing components (including frames) to improve strength and decrease weight. Litespeed was one of two innovators in respect of titanium frames. Its history can be traced to the small Lynskey family run machine shop in Tennessee. One of the sons suffered from a running injury and was advised to take up cycling. Unimpressed with the bikes for sale in the local bike shop, the three brothers 'tinkered' around on weekends in their machine shop trying out different frame options. They ended up using some leftover titanium tubes from a chemical job and a basic titanium frame prototype was constructed. While the local bike shops were not impressed, they took their new frame to a trade show in California and started producing some frames under the brand of Litespeed as orders started coming in.

Interestingly, present at the same tradeshow in California was another embryonic titanium frame developer – Merlin Metalworks. Started by Gwyn Jones, Gary Helfrich, and Mike Auspurger in Massachusetts, Helfrich was at the time working for Fat Chance Cycles where he had put forward the concept of a titanium frame. Getting nowhere, he teamed up with known-frame designer, Auspurger, with Jones' contribution being the sourcing of titanium tubing from the aerospace industry given his background. Auspurger left the partnership early, but Helfrich continued to drive operations out of the basement of his house to create Merlin Metalworks' first titanium frame.

Titanium wasn't the only new material being used for frame production. While aluminium is not as strong as steel, doubling the diameter of the tubing will result in a 16-fold increase in strength. The first oversized aluminium tubed frame was developed under the name of Hi-E Engineering in Tennessee. Harlen Meyer was an aircraft engineer and used this background in working with aluminium and tungsten inert gas (TIG) welding to develop a bicycle for his son who was a competitive cyclist. Only 15 frames were produced in his home workshop, but it created a foundation for future aluminium frames (and other aluminium components).

In comparison to some of the basement/garage/personal workshop developed frames, the development of carbon fibre bicycle frames relied upon more corporate development facilities. For example, the first monocoque frame (single piece carbon fibre construction) came from Kestrel. Started by ex-employees of Trek and specialists from the aerospace industry, the scale and complexity of carbon fibre production was beyond what could be undertaken in a garage or small-scale workshop that did not have corporate backing. Similarly, other less common exotic materials required a corporate setting. Kirk Precision in the UK developed a magnesium bicycle frame. Frank Kirk, an automotive engineer, left Ford to create a small range of performance-oriented bicycles using the die cast method to create the magnesium structure. The beryllium frame was created by integrated beryllium company Brush-Wellman under the brand name of American Bicycle Manufacturer. Further, a unique product by Ballau Structures used an exceptionally thin-walled titanium frame where the rigidity was provided through the same honeycomb material used in the B2 Stealth Bomber. Like much of the complex carbon fibre frames that used production techniques such as bladder moulding and CNC machining to cut the pre-peg carbon sheets for joins, the cost and complexity of some exotic material frames required significant funding precluding their development in a DIY lab setting.

4.4. Moving components

The moving components on a bicycle centre on the gears and the brakes. They include the brake levers, the callipers (or other braking structures such as a drum or disc system) and brake pads, chain rings, chain, cranks, bottom bracket, rear cassette (gear cogs), front and rear derailleur, and the gear levers. Known amongst cyclists as a component set, the production of these moving components has been dominated by large international firms such as Shimano, Campagnolo, Mavic, Sachs and Suntour. Consolidation and closures of some of the smaller players (eg Suntour and Gallo) through the 1980s and into the 1990s saw Shimano at one stage control over 80% of the market. As the moving components are expensive, relative to the total cost of a bicycle, these large firms have undertaken their R&D internally.

In the last decade, the major change has been the growth of SRAM. The original innovation that spawned the success of SRAM was the Gripshift gear changer that was designed and prototyped by engineer Sam Patterson. Working for a San Diego engine manufacturer, Patterson was keen to develop a gear changing system for mountain bikes that did not require the rider to remove their hands from the handlebars. As such, outside of work, Patterson designed a gear shifting system that wrapped around the handlebars and was indexed so that a single click on the system would shift one gear up or down according to the direction it was turned. Patterson then met Stanley Day on a ski trip via his brother who had attended graduate school with Day. Intrigued by this untested design that Patterson had put together, Day organised a group of investors to bring the idea to fruition, creating the basis for what is now SRAM.

4.5. Other components

John Rader, the developer of what was to become known as the Aheadset, came to the industry with a background in the race car industry (as did numerous members of the family). His family had its own workshop where they could work on their cars at home in Texas and it was here that Rader developed a radically different headset (joining the stem and handlebars to the front forks to allow for steering). He later pitched the idea to Peter Gilbert of Dia-Compe (which took on the idea to manufacture the product under the Dia-Compe brand).

The other innovative headset was developed by Chris King. He had previously done some work at a local bikeshop and was encouraged to make a much lighter headset, but after college he went to work for a medical instrument company that made air tools for surgeries. When products came back under warranty, he took these apart to extract the bearing sets. He managed to salvage about 200 sets that would otherwise be discarded and then used these as the basis of building a new style of headset. His initial workshop would have been not much more than 20 square metres. Four years later, the need for expansion saw him rent a disused roller-skating rink and move into other bicycle components including frames.

Geoff Ringle also worked in the medical devices industry designing and fabricating new products (including holding a patent for a key component in a heart pump). A constant 'tinkerer', he operated from a small workshop out of hours developing stems and cranks until he made the shift into full-time bicycle component production, ending up designing and handlebars, seat-posts, hubs and headsets.

Ex-USA road and track racer Bill Shook started tinkering with components after his competitive cycling career ended. With a Masters in Mechanical Engineering, following some work in the pump industry, he initially developed a lightweight water-bottle cage from a single piece of aluminium. Other aluminium cages existed, but over time, they broke at the weld points. Experience in working with pipe where curves are often superior to welded angles saw Shook take an alternative path that avoiding welding. He subsequently developed an adjustable seat-post (again on the basis of his experience with tubular pipe) in his small workshop. These products were then released for commercial sale

under the brand of American Classic and the operation eventually shifted to larger commercial premises where further components such as hubs were developed.

Finally, in the area of pedals, ski equipment manufacturer, Look, introduced a 'clipless' design (i.e. no cage over the top of the foot) that has been adapted by all major pedal manufacturers. One of the more innovative designs has been the Speedplay pedal which allows a degree of rotation on the pedal without becoming unattached. The story behind this innovation was that Richard Bryne was invited by mechanical engineer Steve Ball to be the rider for a specific competition for which Ball was developing a new design. The two of them started working out of Ball's garage on innovative designs for different frame designs and specific components. As part of this 'apprenticeship', Bryne learnt to mill and lathe billet aluminium. Bryne's regular day job changed over time from promoter to setting up a fencing company, but he kept coming back to bicycle components. Working with Ball, Bryne developed and patented what is now the Speedplay pedal design. However, after 22 rejections from potential manufacturers and 2 years after being granted a patent, Bryne and his wife established Speedplay and started to manufacture the component themselves.

5. Discussion

Our findings have highlighted that the bicycle industry has benefited from numerous innovations across virtually all components in the product architecture, and DIY labs played an important, but albeit limited, role in this technological advancement as these innovations often drew upon technical knowledge that originated in other 'super-spreader' sectors. While the 15 innovations we identified are not a large proportion of the total innovations, our case analysis nonetheless illuminates how the fundamental principles of DIY labs - placing research and development activities in hands of individuals outside of a corporate setting - does occur in the bicycle industry and has an impact upon its technical trajectory.

Our findings allow us to make three important contributions that reaffirm and extend existing scholarship on DIY lab entrepreneurship. First, turning to our first research question - what role do DIY labs play in inter-industry technology and knowledge spillover? - we highlighted two ways in which DIY labs contributed to the technological advance of the bicycle industry. The first group of innovations (a total of 5) were developed intra-industry by individuals who were bicycle industry enthusiasts and already located in the industry, but lacked the financial resources to establish a well-funded and formal enterprise. For example, Terry studied mechanical engineering and worked as an engineer for large industrial conglomerates, and it was her engineering background and interest in the sector that actually put her in a position to make specialised bicycle frames for women. Working out of her basement kept cost low until she made the move to work full-time on this business. These cases were good example of bricolage where the entrepreneur operates frugally and 'makes do' with their limited resources (Senyard et al., 2014; Michaelis et al., 2019) and aligns with much of the DIY lab literature that refers to the limited capital of many DIY ventures and the fact that they are often self- or crowd-funded (Alrich, 2014; Sarpong et al., 2020).

Probably more interesting were the second group of 10 innovations - which were developed inter-industry as DIY innovators appropriated knowledge or technology from other high-technology industries and combined and applied it in new ways in the bicycle sector. For example, Meyer, who as an aircraft engineer was experienced at working with aluminium (the dominant construction material in respect of aircraft) and TIG welding, and was able to build the first aluminium bicycle frames in his home workshop. Taken together, these two approaches to the development of innovation highlights the importance of both intra- and inter-industry knowledge spillovers.

Across our sample, we noted a number of examples of innovations arising from inter-industry knowledge spillovers originating in other

high-technology sectors. In many cases, the DIY developers had extensive prior knowledge and experience in a variety of industries with the car racing and automotive sector being heavily represented. Often, these super-spreader industries featured large multi-national firms who engaged in many, if not all, segments of the industry value chain and across a number of different technologies. The motor vehicle industry, for example, relies upon a range of materials and different production processes and features high-levels of consolidation. The presence of super-spreader source industries is perhaps unsurprising as prior research has suggested that innovations in the bicycle industry have drawn upon technology originating from the aerospace, chemical, motorcycle, automotive and defence industries (Meissner et al., 2020). Our findings also indicated that inter-industry knowledge spillovers featured the integration and application of diversified knowledge sets which emerged from a combination of different source technologies and needed to be integrated in new and novel ways (Battke et al., 2016). While the existing literature is somewhat inconclusive, diversified knowledge is central to novelty in the innovation process (e.g., Arthur, 2009; Schilling and Green, 2011). In our case analysis, all of the innovations arising from inter-industry knowledge spillovers were developed by individuals who had extensive prior experience (normally as engineers) in other unrelated industries. Our findings show numerous examples of knowledge bases relevant to different technologies (in different industries) being adapted and combined with specialised bicycle industry knowledge to create recombinant sets of knowledge that could then be applied to the recipient sector.

Second, in our case analysis, DIY labs were predominantly focused on commercializing entrepreneurial opportunities rather than extending the underlying science. Whether it was working with existing carbon fibre strands and/or sheets to mould them into a disc wheel rather than a race car nose box, or collecting discarded bearing sets from medical equipment to be repurposed, the DIY labs focused on using existing knowledge from another sector, combining it with bicycle industry knowledge, and applying it in new ways to create new business opportunities. Thus, the DIY labs became an experimental transition point between identifying a business opportunity and finalising a business concept (Battke et al., 2016; Bhawe, 1994). The archival sources we employed often used the terms 'tinkering and experimentation' as DIY developers experimented and re-experimented without facing the commercial constraints of a typical corporate setting. The use of DIY labs as a space for experimentation and refinement rather than extending basic science perhaps makes sense given the limited capital base that existed. Fully-resourced R&D programs were simply not realistic given that these entrepreneurs were essentially engaged in bootstrapping (Ebben and Johnson, 2006).

As the technologies relied upon by the DIY innovators were not proprietary or 'cutting-edge', their focus was on repurposing the knowledge for the bicycle industry context. The key role of the DIY lab was to allow the experimentation process to occur unfettered rather than facing the commercial constraints that are likely to present themselves in a corporate setting. The migration of human capital and knowledge across industry boundaries provided the basis for the business opportunity, whilst the DIY laboratory presented a space for entrepreneurial activity to occur with few constraints to propel forward the eventual refinement of a business concept (Fig. 1)

In comparing these 15 cases to the other 83 innovations in the sample where DIY labs did not feature in the innovation process, we identified three key themes. First, the innovation development process was considerably more structured. Many innovations emerged from specific research projects that built upon existing knowledge and thus created something of a technology trajectory. Interestingly, the later innovations that were developed by many of the firms discussed in the previous section followed this same path. For example, Zipp and HED continued to innovate in the area of carbon fibre aerodynamic components (primarily wheels). These innovation efforts were far more defined, structured and funded compared to the 'tinkering' that was

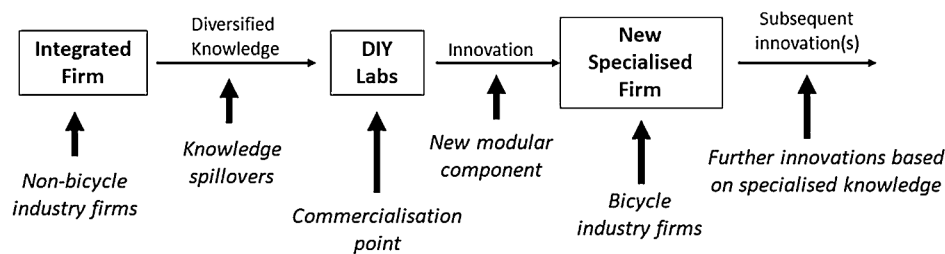


Fig. 1. DIY labs as a central transition point between industries.

often observed in respect of DIY labs.

Second, the size and scope of the firms already operating in the industry meant that many firms produced multiple components, often utilising a variety of different technologies. Whilst the number of radical innovations were limited, the fact that these firms had the capacity to innovate across multiple components and thus alter the architecture of parts of the bicycle. For example, Shimano was able to alter gear levers, brakes levers and the derailleurs (front and rear) to develop an integrated gear changing system that operated within the brake lever system. Such an innovation was simply beyond the scope of possibility for the SMEs that utilised DIY labs and entered the industry on the basis of an innovation in a single component. And third, exaptation of technologies from other industries did not occur just through DIY labs. Firms with a background in other industries (eg Look from the ski industry, EDO Fibre Science from the defence industry) often took a technology developed in one industry and leveraged this into the bicycle industry – sometimes through a new subsidiary. Thus, DIY labs were just one model for exaptation in the bicycle industry.

Turning to our second research question - how does the technological and institutional context affect the type of innovations that emerge? - our findings extend existing research on the nature of exaptive innovations – the process whereby technologies developed for one purpose are repurposed for an entirely different role (Andriani et al., 2017). To date, the exaptation literature is dominated by examples of firms co-opting a technology from one industry to another – for example, the magnetron in radar being used to create the first microwave oven by Raytheon (Beltagui et al., 2020; Mastrogiorgio and Gilsing, 2016), Corning's specialised glass products being used as a basis for the creation of fibre optics (Cattani, 2005, 2006) or Pfizer's Viagra initially being developed as an antihypertensive drug, but was subsequently found to be useful in respect of erectile dysfunction (Andriani et al., 2017). In comparison, the exaptive innovation developed for the bicycle industry was created in an organisation separate from the original source. Thus, in our case analysis, the capacity for DIY lab innovators to leverage inter-industry knowledge spillovers to create exaptive innovations is, at least, partially a function of the technological environment (eg, product architecture) that supports knowledge spillovers across industry boundaries.

While diversified knowledge has been linked to increased technological variety or novelty (van den Bergh, 2008; Schoenmakers and Duysters, 2010), the type of exaptive innovations that DIY labs commercialised is surprisingly under-elaborated. However, our data allows us to advance an understanding of the types of innovation that DIY labs may engage in. By drawing upon Henderson and Clark (1990) innovation typology, our findings indicate that DIY labs engaged in incremental exaptive innovation, rather than radical or architectural innovation, however this finding runs counter to some existing literature (Aldrich, 2014; Anderson, 2012; Kwon and Lee, 2017). As the bicycle is a modular product design, where each component is designed independently of each other and connects to the product architecture through a defined set of interfaces (Fixson and Park, 2008), the modular character of the bicycle encouraged new entrants to enter the industry by permitting innovation to be enveloped within a single modular component that could be developed in isolation from the rest of the

industry (Burton and Galvin, 2018). In comparison, the design of less modular products such as an Apple iPhone make it difficult for firms to contribute components to the product system without more formalised links to the industry value chain (e.g. even app developers cannot release new apps unfettered via the App Store without Apple's approval). As such, modular product architectures not only enable innovation to be isolated within structures such as DIY labs, but the design also allows individuals or small enterprises to enter an industry by focusing upon a single component at a time, such as a water-bottle cage or seat-post which may be the starting point for a successful new enterprise. Thus, we suggest that DIY labs may be an important enterprise for modular exaptation (Andriani and Carignani, 2014) when the technology from one industry is able to be coopted into an industry due to the modularity of the product architecture.

The issue of exaptation is often linked to the notion of serendipity (Dew, 2009; Meyers, 2007) and indeed in the cases discussed here, there may have been an element of serendipity involved – a lucky conflation of people, ideas and circumstances. The shift between industries for most of the innovations could be viewed as a matter of luck (versus foresight), but it is possible that this is when DIY labs are most useful – when people find themselves in a position to take advantage of a particular knowledge set that will allow them to enter a new industry, but lack the experience and connections in the new industry to raise capital and run the new venture in a more formalised form. This does not mean that DIY labs do not have an important role to play – even if serendipity was perhaps an important part of the innovation story. The innovations developed align with the continuing 'foresight versus luck' debate (Barney, 1997; Cattani, 2006) and while some degree of serendipity may have been present, it was also clear that the DIY innovators were on the lookout for opportunities. For example, Saergent was planning to develop a race wheelchair; Chris King may have worked in the medical devices industry, but had an interest in bicycles from his days of racing and working in a bike shop. The innovation literature is full of examples of 'luck' (see Garud et al., 1997; Meyers, 2007), nonetheless we have found that DIY labs played an important role as incubators of new innovations that often evolved on the basis of knowledge acquired from other industries.

5.1. Policy implications

Given the role that DIY labs played in the development of incremental innovations in the bicycle industry, there are potential policy implications for governments seeking to grow local industries. The DIY labs form an important transition point between the large integrated firms in high-technology sectors that undertook significant research and the eventual commercialisation in recipient sectors of some of the knowledge spillovers that originated in these large firms. As spaces for experimentation and commercialisation that adapted diversified knowledge from one industry and applied it to another industry, DIY labs may be a low cost, low risk approach for innovation generation and diffusion in a new industry.

DIY labs were not responsible for radically transforming product architectures or industries, but they did contribute to economic growth in the immediate region. None of the examples we found in the bicycle

industry utilised large-scale DIY labs in the form that have been established in some regions to support R&D in life sciences (Landrain et al., 2013; Wexler, 2017). Instead, our DIY innovators had to make do with garages, personal workshops and basements. Whilst this obviously did not hamper those that innovated and released a commercially successful product into the market, it is unknown whether there were missed opportunities due to a lack of appropriate development space. Thus, in the same way that collaborative or co-working spaces have been successful in supporting entrepreneurial ventures (Bouncken and Reuschl, 2018; Fuzi, 2015), DIY labs could provide an important support mechanism for budding entrepreneurs. Bringing together a range of diversified knowledge bases from integrated firms into corporate or government-supported DIY labs may even go some way to moving past the incremental innovation that was observed in the bicycle industry, and instead help create the breakthrough and radical innovations that various authors suggest is possible (Aldrich, 2014; Kwon and Lee, 2017).

6. Conclusions

Existing DIY labs literature has to date tended to focus on the traits, motivations and background/expertise of entrepreneurs that utilise home, workshop or other non-traditional spaces to undertake research and development (Baden et al., 2015; Hatch, 2013; Martin, 2015). Suggesting that these DIY labs provide opportunities for the democratisation of science (Kwon and Lee, 2017), they are often positioned as an opportunity to create breakthrough innovations that may address some of the major challenges that sit at the intersection of science and society (Hecker et al., 2018). Given the relative immaturity of the research concerning DIY labs, the issues concerning their role in commercializing knowledge spillovers and their role in linking those industries from which knowledge spillovers originate and the industries into which the new commercialised knowledge is leveraged has not, to date, been a focus of the research.

Our study of the bicycle industry has identified a number of cases of DIY labs driving innovation. Contrary to expectations (see Aldrich, 2014), they did not produce radical or break-through innovations, but rather produced a range of incremental innovations that relied heavily upon the use of alternative materials or the potential for enhanced performance in respect of one or more components. A partial explanation for this may lie with modular design of the bicycle, perhaps making it unlikely for any but the largest firms to drive architectural or radical innovation (Fixson and Park, 2008; Burton and Galvin, 2020). However, what was also observed was that the DIY labs were primarily locations where experimentation could occur as entrepreneurs sought to convert diversified knowledge from other industries into new marketable products. The DIY lab provided the space for relatively open-ended investigation and tinkering outside of the corporate setting where a lack of clarity around the potential for a commercialised product may have been challenging in a more formalised structure. They suffered from a lack of working capital which led them to focus more on the development part of 'research and development', but just as importantly, the DIY labs provided spaces that were not subject to the types of expectations and focused research that would likely be found in more corporate settings. The knowledge that formed the basis for the innovations was general in nature and certainly not proprietary. Entrepreneurs needed to experiment and tinker in a setting that would allow it to be applied in a new industry – something that had not been envisaged by the original developer in the source industry and it was in this setting that DIY labs proved valuable. Thus, DIY labs may not be the engine for growth in transforming industries that some may hope for. They are, however, an important part of the entrepreneurial landscape that play a significant role in pushing the technological frontier of existing modular products.

In the case of the bicycle industry, the presence of DIY labs has fulfilled an important role in providing a flow of innovations into the

industry. Paradoxically, the high level of demand for innovative products in the competition-oriented segment of the market has not driven a massive investment in R&D across the industry, largely due to the scale of this market segment. With knowledge spillovers occurring from the aerospace, chemical, skiing, motorcycle, motor vehicle and defence industries, there are challenges in translating this diversified knowledge from largely integrated firms into novel innovations. Often the absorptive capacity that allows firms to recognise the value of the knowledge does not exist, or perhaps due to its diversified nature it is hard to convert it into a product innovation without an entrepreneur with the appropriate background to commercialise the knowledge. DIY labs are therefore a transition point for knowledge spillovers, where diversified knowledge is commercialised as it moves from an integrated firm to a more specialised one that is later able to leverage this specialised knowledge for further developments in the same technology.

It should be noted that the case histories of innovations in the global bicycle industry were not necessarily representative of all innovations that occurred across the time period considered. The innovations were almost entirely skewed towards the 'performance' segment of the market. However, prior research (Galvin, 1999; Yan and Hu, 2008) has indicated that innovative activity tends to occur in this segment before diffusing to other value-based segments across time. In addition, the archival materials accessed were only those that were available in English and they tended to focus upon the higher priced and more performance-oriented segments. Thus, the data is almost silent on any possible technical advances made by Taiwanese and Chinese firms that operate in the more price-sensitive market segments. As such, there are possibly product innovations by firms in the Far East that were not captured within this study.

Looking forward, the positioning of DIY labs is an area that offers both theoretical and policy opportunities. While the bicycle industry did not see entrepreneurs use formalised DIY lab space that was supported by government or corporate backing, this is an emerging trend – especially in the life sciences (Landrain et al., 2013; Wexler, 2017) – and one that may support technological development, entrepreneurship and the economic opportunities that flow from innovation support. In the same way that collaborative spaces to support start-ups benefit the local economy, research on the role that more formalised DIY labs provide to effective commercialisation of diversified knowledge spillovers is a worthy area of investigation.

CRedit authorship contribution statement

Peter Galvin: Methodology, Conceptualization, Writing - original draft, Writing - review & editing. **Nicholas Burton:** Conceptualization, Writing - original draft, Writing - review & editing. **Richard Nyuur:** Writing - original draft, Writing - review & editing.

Declarations of Competing Interest

None.

Appendix 1. Data sources

Trade publications

Pedal Pushers Guide
Bicycling Buyers Guide
Colorado Cyclist Catalogue
Cycling Buyers Guide
Cycle Express Catalogue
Cycling World Buyers Guide

Magazines for industry participants and sport enthusiasts

Bicycling
Bicycling Australia
Bicycling World
Cycling World
Mountain Bike
Mountain Bike Action
Performance Cyclist
Velo News

Books

Bicycle: The History
Bicycle History: A Chronological Cycling History of People, Races and Technology
A History of Bicycles: From Hobby Horse to Mountain Bike The Bicycle Book

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